REAL-TIME GPS MONITORING OF ATOMIC FREQUENCY STANDARDS IN THE CANADIAN ACTIVE CONTROL SYSTEM (CACS)

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Abstract

Ten Real-Time Active Control Points (RTACP) across Canada continuously monitor all GPS satellites in view and generate wide area GPS corrections with an update rate of 2 s. Dual frequency high precision geodetic GPS receivers using free running atomic frequency standards (masers, Cs and Rb) provide pseudorange and phase measurements at 1 s intervals. Ionosphere-free, carrier-phase-filtered pseudorange data are combined with rapid GPS satellite orbit predictions and RTACP coordinates in a least-squares adjustment to determine satellite and station clock offsets with respect to a virtual reference clock (VRC). The VRC is maintained as a weighted mean of RTACP long-term clock models. The VRC is related to the mean GPS system time using a long-term linear clock model with correlation time of a few days and it is traceable to UTC (NRC). This approach mitigates the effects of instabilities of individual RTACP clocks, eliminates clock discontinuities, and provides VRC stability better than 10^{-14} for time intervals greater than 1 day. The system provides continuous RTACP clock synchronization with RMS residuals in the range of 0.1-0.5 ns and real-time GPS satellite clock corrections with RMS residuals in the range of 0.3-0.8 ns. The quality of the real-time results are presented and discussed.

INTRODUCTION

The Geodetic Survey Division operates the Canadian Active Control System (CACS). It comprises a Master Active Control Station (MACS) and a network of continuously operating GPS data acquisition stations, called Active Control Points (ACPs), which are distributed across the Canadian landmass and track all GPS satellites in view. The GPS data from several ACPs are contributed to the International GPS Service (IGS). The NRCan Analysis Center processes the Canadian and a portion of the global IGS data to generate daily precise GPS satellite ephemerides and clocks, earth orientation parameters (EOP), and ionospheric, tropospheric and terrestrial reference frame information, as well as rapid GPS orbit predictions [1].

Ten of the CACS tracking stations (Fig. 1) have been enhanced to facilitate real-time data communication with the processing center, forming the Canada-wide network of Real-Time ACPs (RTACPs). Data from these RTACPs are available at the Real-Time Master Active Control Station (RTMACS) in less than two seconds for the computation of wide area GPS corrections, which is known

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as the Canadian GPS•C service. The system architecture, data communication infrastructure, and the real-time application software are described in [2].

The RTMACS configuration, processes, and GPS•C positioning performance are described in [3] and [4]. A state-space domain algorithm is used to compute real-time corrections to the broadcast satellite orbits and clocks using ionosphere-free, carrier-phase–filtered pseudoranges, predicted GPS satellite ephemerides, and the RTACP station coordinates. The RTACP receiver clock offsets and a grid of vertical ionospheric delays for a single-layer model of the ionosphere are also generated. The GPS•C service facilitates real-time GPS positioning of about half a meter horizontally and a meter vertically, when using geodetic quality receivers. All GPS receiver and satellite clock offsets are determined with respect to a Virtual Reference Clock (VRC), which is maintained as a weighted mean of long-term models of selected RTACP receiver clocks.

A description of the real-time GPS data processing, clock monitoring, and the VRC maintenance is presented below. The real-time station and satellite clock results are compared with the precise geodetic post-processing results produced by the NRCan Analysis Center using the global IGS network data. Allan variances of the de-trended real-time RTACP receiver clocks and the VRC are also presented.

REAL-TIME GPS DATA ACQUISITION, COMMUNICATION, AND PROCESSING

The RTMACS and RTACP network is based on Hewlett-Packard UNIX servers, dedicated frame relay communication facilities, and the Real-Time Application Platform (RTAP) technology [2]. The RTAP has been used to implement a real-time distributed database, which uses a scan system for process control, data acquisition and communication, a calculation engine to automate data processing within the database, and an event manager to handle real-time events, inter-process communication, and run-time priorities. Land and satellite communication links between the RTMACS and the RTACPs support TCP/IP protocol with the maximum communication delays of less than 0.5 and 1.5 seconds respectively. The necessity to use the satellite communication links in order to provide Canada wide coverage is limiting the present GPS•C service update rate to 2 seconds.

The pseudorange and carrier-phase data represent the time delay between the GPS signal transmission from the satellite and its detection at the receiver, as measured by the difference of the corresponding satellite and receiver clocks. This delay can be expressed as the sum of the geometric satellite range delay, the tropospheric delay, and the ionospheric delay; it also includes the satellite and receiver clock misalignment, the Selective Availability (SA), and relativistic effects. In general, the pseudorange measurements show a noise of about 50 cm, whereas the noise of the carrier-phase data is at a centimeter level if its cycle ambiguities can be correctly resolved.

At two-second intervals, RTACP observation history of the latest five epochs is retrieved from the RTMACS database using criteria which minimize latency, maximize coverage, and assure input from RTACP stations with high quality atomic frequency standards. All the GPS data for the selected epoch are corrected to the first order for the ionospheric delay by combining the L1 and L2 measurements to mitigate any long-term ionospheric biases. However, the ionosphere-free combinations show increased short-term noise in comparison with the L1 data. The pseudoranges are then filtered using carrier-phase by averaging the differences between the ionosphere-free pseudorange and the carrier-phase measurements and by integrating the ionosphere-free carrier-phase. At the start of a satellite pass or when a cycle slip is detected, the averaging and integration are restarted. As the average converges to the ionosphere-free carrier-phase ambiguity, the noise of the filtered pseudoranges decreases to about 5

cm. However, the averaging takes some time to converge, mainly due to the increased pseudorange noise for satellites at low elevation angles. The detection of cycle slips is also important for the quality of the filtered data. Only filtered pseudoranges below the noise threshold for the determination of ionosphere-free carrier-phase ambiguities are used in the subsequent processing.

GPS satellite positions, which are interpolated from predicted ephemerides available at 15-minute intervals, and the known RTACP station coordinates are used to compute the geometric satellite ranges in the observation equations. The relativistic corrections are applied to and the tropospheric delays are removed from filtered pseudorange observations using the Hopfield model for the corresponding satellite elevation angles. In this way, only the GPS satellite and the RTACP receiver clock corrections remain as unknowns in the observation equations, which are solved in a least-squares adjustment. The filtered pseudoranges are assigned weights proportional to the satellite elevation angles, and the least-squares adjustment is constrained using *a priori* information obtained by RTACP receiver clock modeling, as described below.

STATION AND SATELLITE CLOCK MODELING

Polynomials of the first and second order are being used to model both the RTACP receiver and the GPS satellite clock offsets with respect to the system reference clock. Real-time clock model parameters are updated using a sequential scheme with clock offsets weighted as a first-order Markov process according to their age and a given correlation time. Two models are maintained for each of the receiver and satellite clocks to follow their short and long-term behavior. The short-term models are used to provide *a priori* estimates of the receiver and satellite clock offsets in the least-squares adjustment.

First-order polynomials have been used for the RTACP receiver clocks with typical correlation times of a few minutes and a few days for the short-and long-term models respectively. Figure 2 shows the least-squares updates to the short-term RTACP receiver clock models, which reflect the short-term performance of the external frequency standards used and the GPS data noise. These updates for RTACPs with H-masers are mostly well within a 0.5 ns range, whereas for the RTACPs with Cs and Rb frequency standards are generally within 1 and 0.8 ns respectively.

Second-order polynomials have been used to model the GPS satellite clocks with correlation times of a few seconds and a few days for the short-and long-term models respectively. The short-term satellite clock models also include the effects of Selective Availability (SA). Figure 3 shows the least-squares updates to the short-term satellite clock models, which are generally within 0.5 ns, but the lack of pseudorange data and their higher noise for low satellite elevations at the beginning and the end of each satellite pass are apparent.

THE VIRTUAL REFERENCE CLOCK

There are two basic approaches to the definition and maintenance of the system reference clock: (1) to use one of the receiver clocks in the network as the system reference clock or (2) to define a Virtual Reference Clock (VRC) as a mean of selected receiver clocks in the network. The first approach is relatively simple to implement, but makes the system completely dependent on a single station and its performance, which is from an operational point of view highly undesirable. The second approach requires an efficient way to deal with sudden changes in individual receiver clock behavior in order to maintain the VRC stability. The VRC stability of the real-time CACS is controlled in two steps:

- In the first step, the least-squares estimation of the short-term RTACP receiver clock model updates is controlled using *a priori* weights reflecting the short-term model noise levels. Each RTACP receiver clock weight is limited by a selectable maximum value. RTACP receiver clock discontinuities due to resets are closely monitored and the affected receiver clocks are down-weighted accordingly. No constraints are presently applied for the estimation of short-term satellite clock model updates, although the least-squares adjustment allows for it.

- In the second step, the VRC is generated and updated as a weighted mean using de-trended long-term RTACP receiver clock models. The *a priori* weights here correspond to the departures of individual receiver clocks from their long-term models. The VRC is then referred to the mean GPS system clock by applying the broadcast satellite clock corrections to the satellite clock offsets and using a long-term linear clock model with correlation time of a few days to smooth any undesirable effects of SA and other satellite clock irregularities. "Steering" of the VRC is accomplished by applying the same bias with opposite sign to the appropriate parameters of all the clock models in the system.

The VRC is usually initialized by assigning zero weights to all but one RTACP receiver clock, which uses an H-maser frequency standard. This represents the first step to the realization of the system reference clock as outlined above and the VRC offset and drift with respect to the mean GPS system clock are those of the selected RTACP receiver clock. The VRC is then "steered" in order to be aligned with the mean GPS system clock; this amounts to introducing clock corrections similar to the broadcast clock corrections for all the clocks in the system. Indeed, after this step the long-term satellite clock model parameters show very good agreement with the broadcast satellite clock corrections for all the GPS satellites using Cs clocks and the current PRN13; some modeling enhancements will be required to obtain similar agreement for the older GPS satellites using Rb clocks. The weighting scheme described above can then be introduced with appropriate maximum values with which an RTACP receiver clock is allowed to contribute to the maintenance of the VRC. After a receiver clock reset detection, the RTACP is excluded from the VRC computation for a period corresponding to the long-term model correlation time. The 1 pps from the RTACP receiver at NRC1 is monitored and traceable to the UTC(NRC). Operator intervention and modification of real-time CACS configuration and data processing parameters are efficiently accomplished by means of a graphical user interface to the RTAP database.

The period between November 16 and 22, 1998 has been chosen to show timing results obtained by the present real-time system implementation. From November 16 to 19 the NRC1 receiver clock, which uses the H-4 maser frequency of the Frequency and Time Standards Laboratory of the Institute for National Measurement Standards, was used as the system reference clock. As of November 19, the H-masers at NRC1, ALGO and YELL, the Cs clocks at STJO and ALBH, and the Rb frequency standard at WINN were selected to establish and maintain the VRC. The RTACP receiver clock offsets with respect to their long-term models for the six RTACPs during the entire period are shown in Figure 4. The daily variations of the GPS receiver clocks using H-masers are typically within few nanoseconds, whereas those using Cs clocks show variations of about 10 to 30 ns and those using Rb frequency standards vary in the tens to hundreds of nanoseconds depending mainly on the RTACP environment.

COMPARISONS OF THE REAL-TIME CLOCK RESULTS

The NRCan Analysis Center global GPS products have been using, most of the time, the H-maser-based ALGO receiver clock as the reference clock in daily precise GPS satellite orbit computations, and high quality relative receiver clock offsets are available at 7.5 minute intervals [5]. Comparisons of clock results between independent solutions by the IGS analysis centers and NRCan show agreement at the nanosecond level [6]. The real-time clock offsets were also referred to the ALGO receiver clock to

facilitate direct comparisons. Figure 5 shows the differences between the real-time and the precise relative receiver clock offsets between the stations ALGO and NRC1 and YELL. The biases apparent in the graphs reflect the pseudorange biases explicitly applied to the data from the given stations for the precise NRCan post-processing. The real-time VRC offsets with respect to the mean GPS system time are shown in Figure 6.

Allan variances of the de-trended real-time RTACP receiver clocks for the 3.5 days of data, when the VRC was used, are shown in Figure 7. The stations equipped with H-masers (NRC1, ALGO, and YELL) consistently show the best clock performance. The stations using Cs clocks (ALBH and STJO) have better long-term performance than the stations with Rb frequency standards (WINN, PRDS, and SCHE), which show better short-term stability. The frequency of the Cs clock at CHUR was adjusted on November 21 and as a result the receiver clock shows poor long-term performance. The VRC, which represents the common reference, clearly shows the best of all performance with the stability better than 10^{-14} for time intervals greater than 1 day.

CONCLUSION

The GPS•C service of the Canadian Active Control System has been implemented to facilitate Canada wide real-time positioning and navigation with better than 1-meter accuracy. Ten RTACPs and the RTMACS form a distributed computer network using frame-relay land and satellite communication links. The GPS satellite and the RTACP receiver clock corrections are computed every 2 seconds with a latency of about 3 seconds and maintain real-time synchronization of all the clocks in the system at the nanosecond level with respect to the VRC. The VRC is realized as a weighted mean of selected RTACP receiver clocks and shows better than 10^{-14} stability for time intervals greater than 1 day. Comparisons with precise post-processing clock results produced by the NRCan Analysis Center show agreement at a few-nanosecond level.

ACKNOWLEDGEMENTS

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REFERENCES

[1] P. Tétreault, R. Ferland, J. Kouba and J. Popelar, "NRCan (EMR) Analysis Center 1997 Annual Report to the IGS," *1997 Annual Report, Volume II, International GPS Service for Geodynamics*, IGS Central Bureau at Jet Propulsion Laboratory, Pasadena, in preparation, 1998.

[2] M. Caissy P. Héroux, F. Lahaye, K. MacLeod, J. Popelar, J. Blore, D. Decker, R. Fong, "Real-Time GPS Correction Service of the Canadian Active Control System," Proceedings of the 9th International Technical Meeting of The Satellite Division of the Institute of Navigation, ION GPS-96, September 17-20, 1996, pp. 1787-1791.

[3] F. Lahaye, M. Caissy, P. Héroux, K. MacLeod, J. Popelar, "Canadian Active Control System Real-Time GPS Correction Service Performance Review," *Proceedings of the National Technical Meeting of the Institute of Navigation*, Santa Monica, USA, January 14-16, 1997, pp. 695-698.

[4] S. Skone, M.E. Cannon, K. Lochhead, P. Héroux, F. Lahaye, "Performance Evaluation of the NRCan Wide Area System," *Proceedings of the 9th International Technical Meeting of The Satellite Division of the Institute of Navigation,* ION GPS-96, September 17-20, 1996, pp. 1787-1791.

[5] R.J. Douglas and J. Popelar, "PTTI Applications at the Limits of GPS," *Proceedings of the 26th Annual Precise Time And Time Interval Applications and Planning Meeting,* 1994, pp. 141-151.

[6] J. Kouba, "1997 Analysis Coordinator report", in 1997 Annual Report, *Volume I, International GPS Service for Geodynamics*, IGS Central Bureau at Jet Propulsion Laboratory, Pasadena, in preparation, 1998.

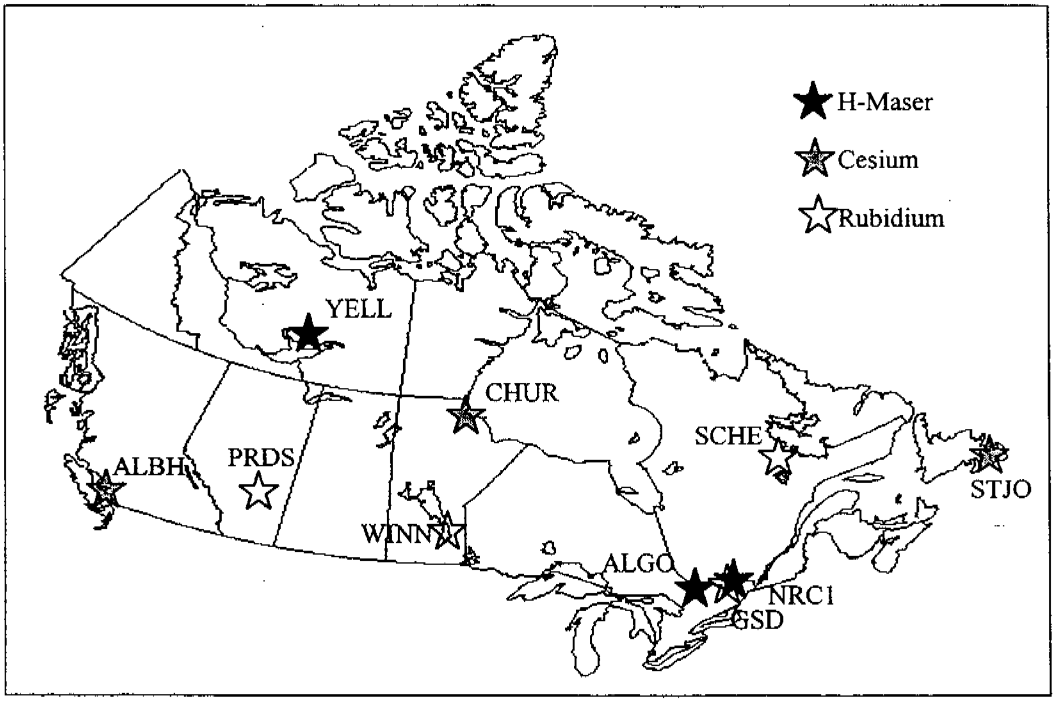

Figure 1: Real-Time Canadian Active Control System network.

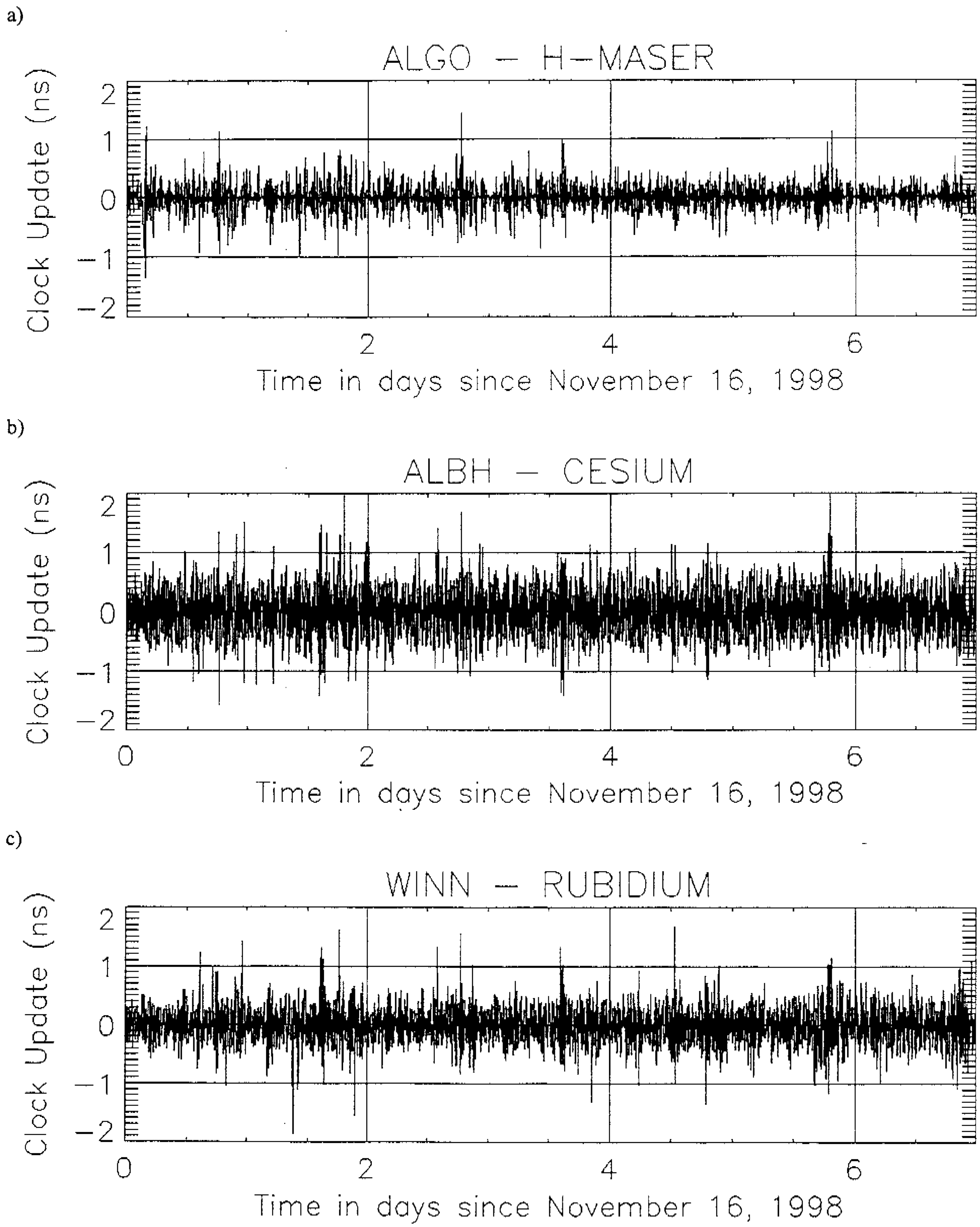

Figure 2: Real-time updates to short-term station clock models for RTACPs equipped with a) H-Maser, b) Cesium and c) Rubidium frequency standards.

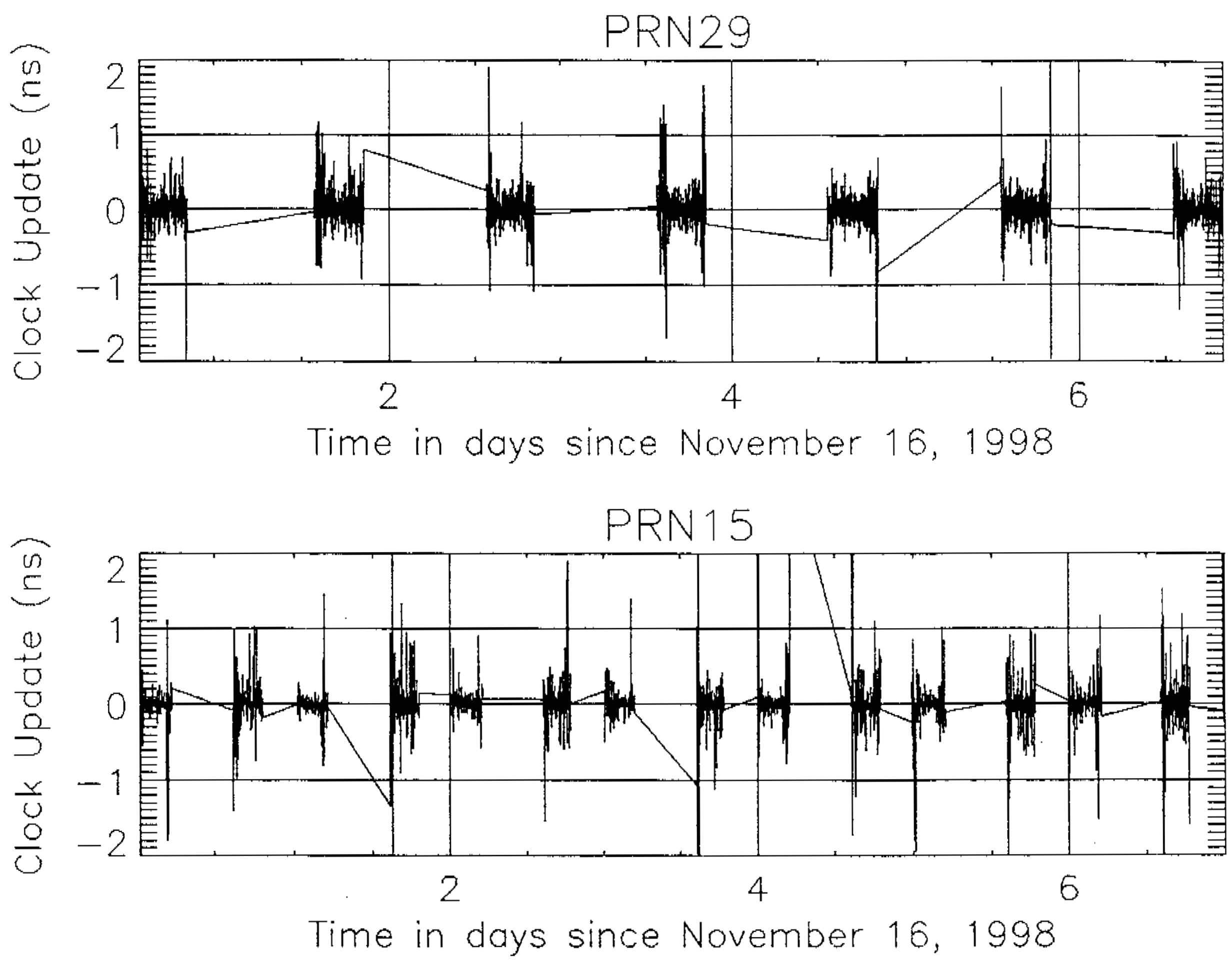

Figure 3: Real-time updates to short-term GPS satellite clock models for a satellite with SA (PRN29) and a satellite without SA (PRN15).

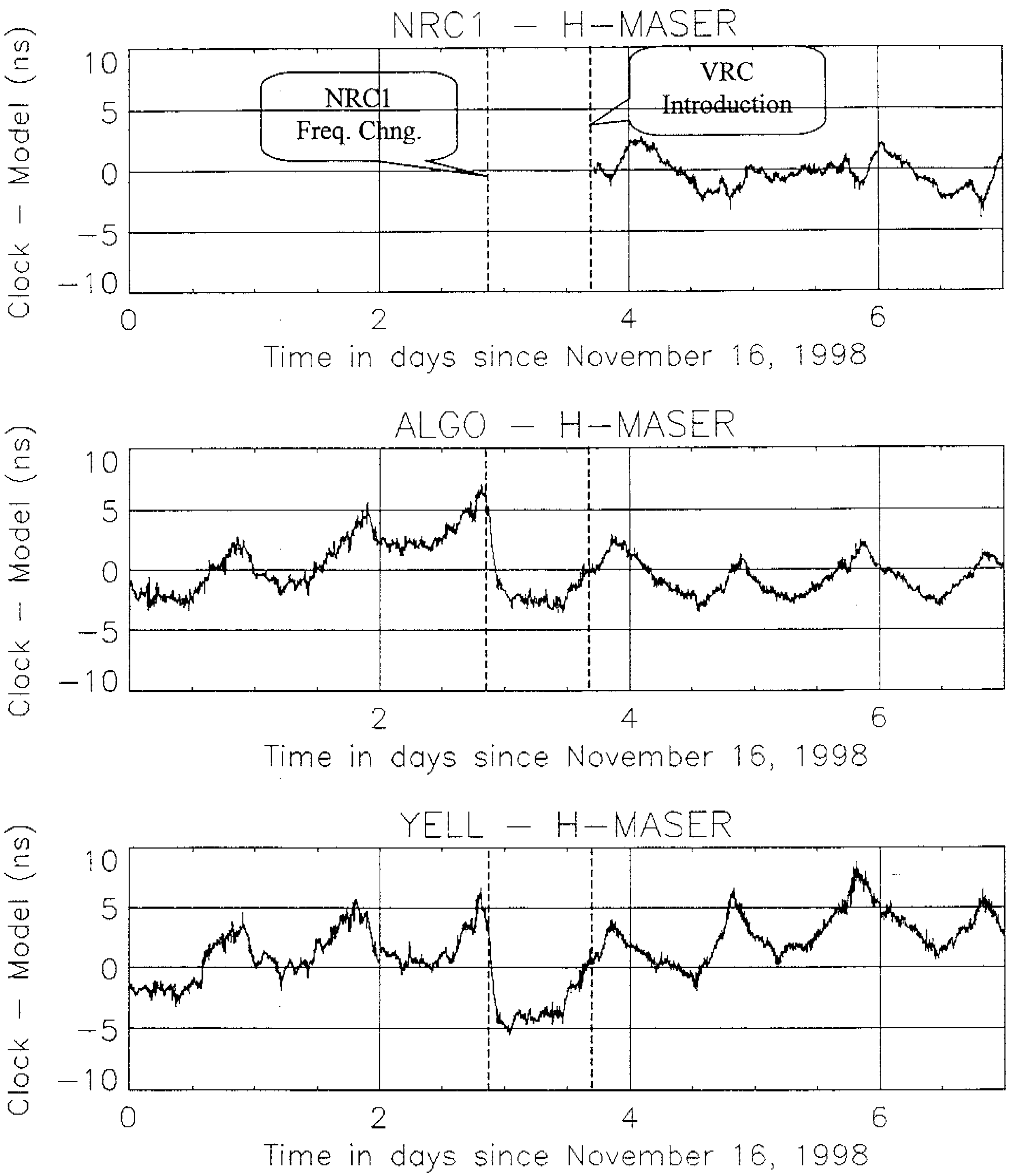

Figure 4a: Real-time RTACP receiver clock offsets for the stations using H-masers with their long-term clock models removed.

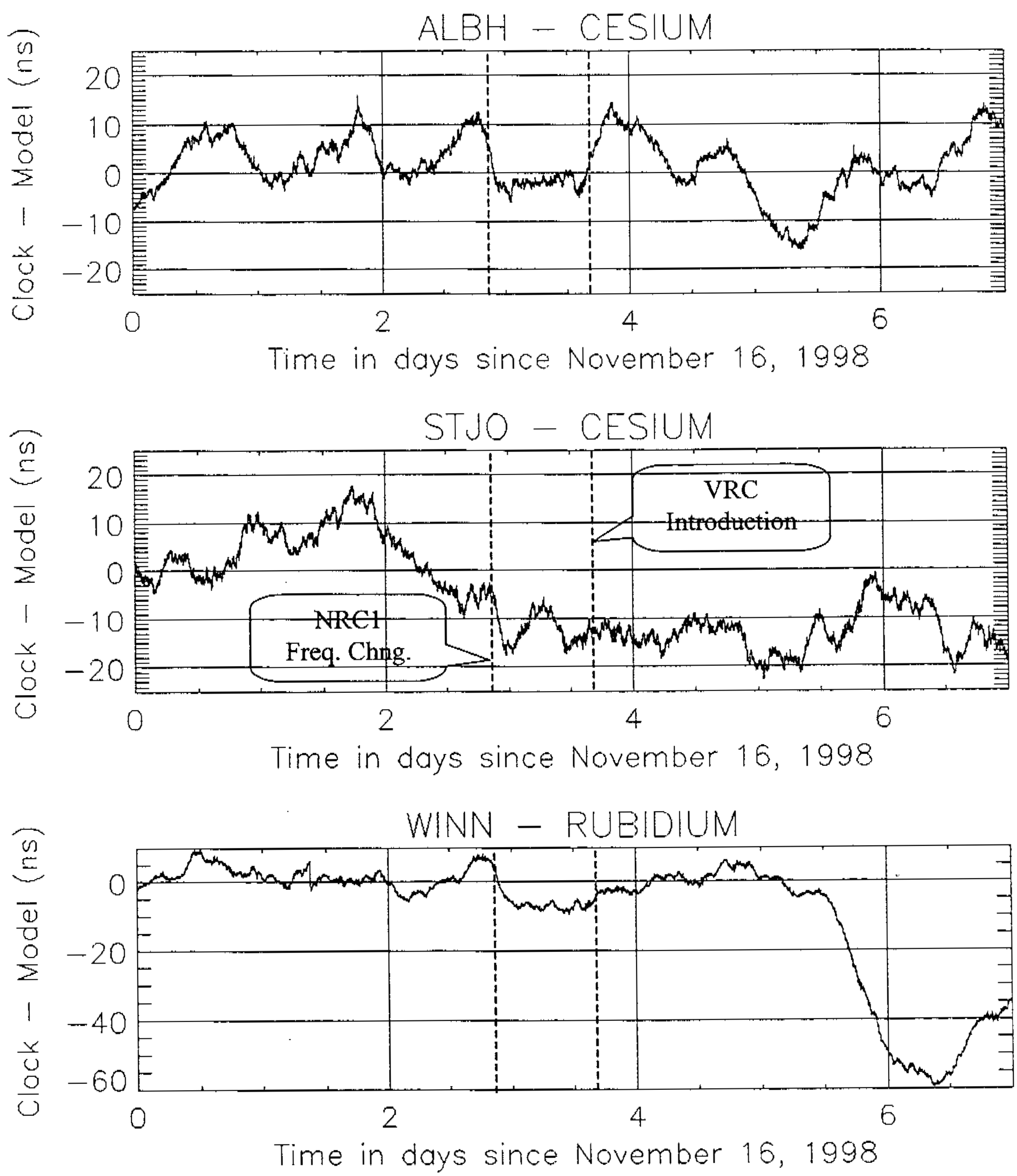

Figure 4b: Real-time RTACP receiver clock offsets for stations using Cs and Rb frequency standards with their long-term clock models removed.

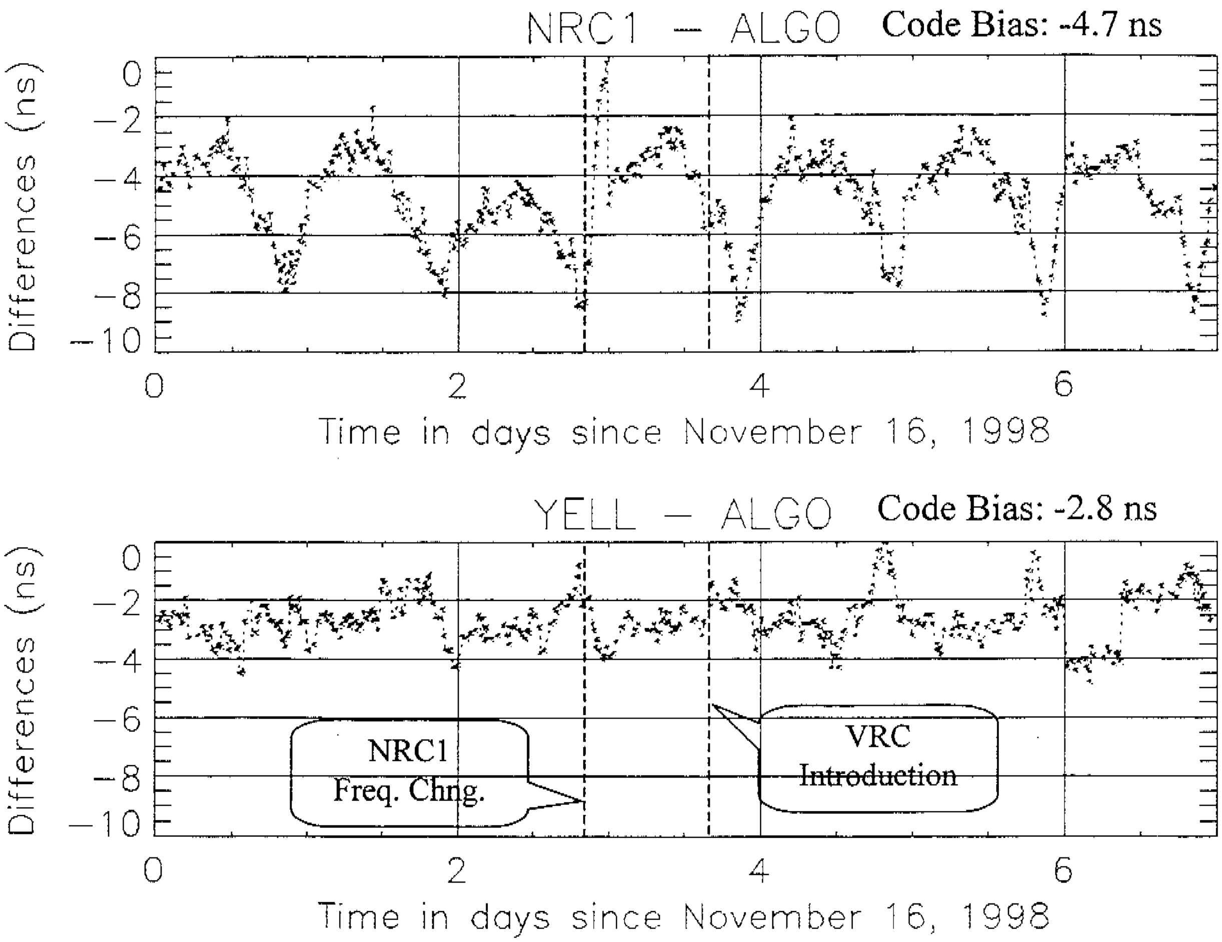

Figure 5: Differences between the real-time and the NRCan precise post-processed relative receiver clock offsets for NRC1, YELL,and ALGO.

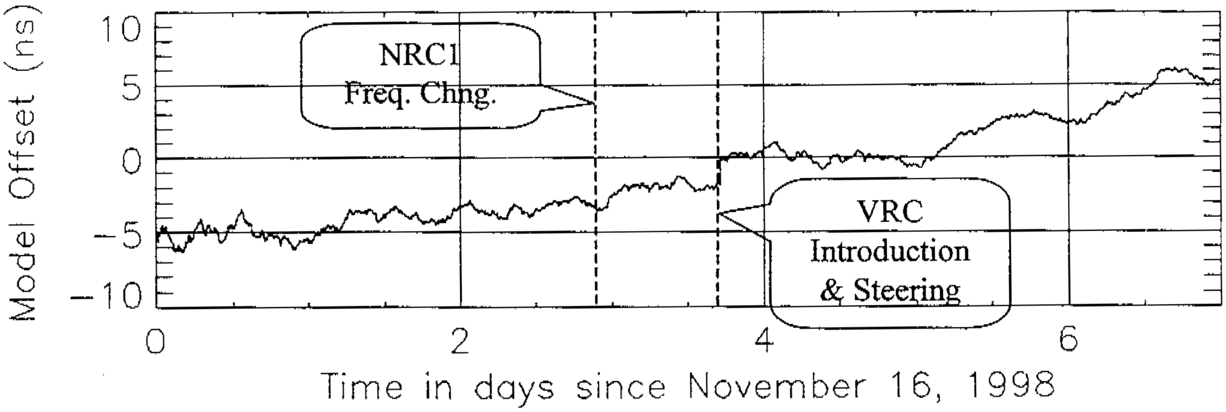

Figure 6: The real-time VRC offset with respect to the mean GPS system time.

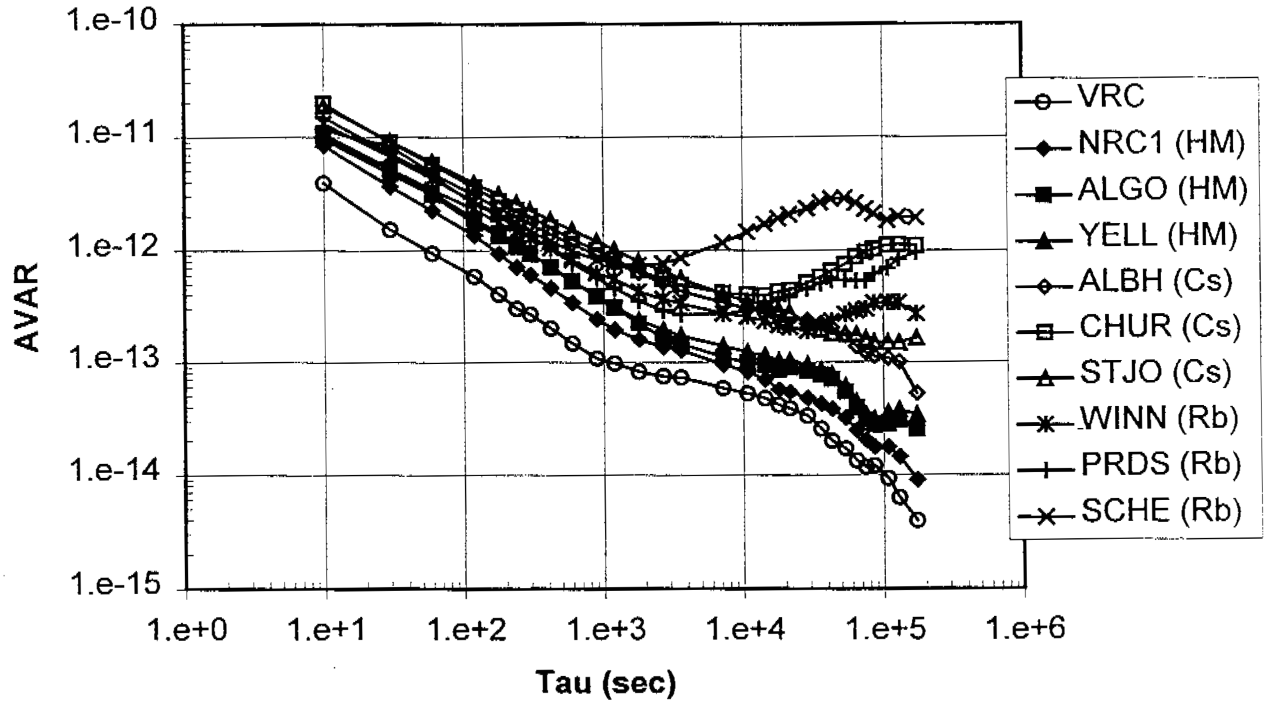

Figure 7: Allan variances of the de-trended real-time RTACP receiver clocks and the VRC.

Questions and Answers

DEMETRIOS MATSAKIS (USNO): I just wanted to point out that the maser that you are referring to at the USNO is a steered maser, and the steering typically varies by a little less than a nanosecond per day. When you do the analysis that you talked about, it might be better to remove all of that. We do have the information to trace the steered maser to an average of our masers, and it is available by anonymous FTP.

By the way we are also looking into changing a bias on it and there could be up to a 40-nanosecond change, gradually introduced, in the near future.